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THE SPENT FUEL SAFETY EXPERIMENT

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SUMMARY

The Department of Energy is conducting an ongoing investigation of the consequences of taking fuel burnup into account in the design of spent fuel transportation packages. A series of experiments, collectively called the Spent Fuel Safety Experiment (SFSX), has been devised to provide integral benchmarks for testing computer-generated predictions of spent fuel behavior. A set of experiments is planned in which sections of unirradiated fuel rods are interchanged with similar sections of spent PWR fuel rods in a critical assembly. By determining the critical size of the arrays, one can obtain benchmark data for comparison with criticality safety calculations.

The integral reactivity worth of the spent fuel can be assessed by comparing the measured delayed critical fuel loading with and without spent fuel. An analytical effort to model the experiments and anticipate the core loadings required to yield the delayed critical conditions runs in parallel with the experimental effort.

PURPOSE

A key issue related to acceptance of spent fuel burnup credit is the verification of the impact of the composition of the spent fuel on the system multiplication factor. The Spent Fuel Safety Experiment (SFSX) directly addresses this issue. A second issue that SFSX addresses is the effect of axial burnup distribution in spent PWR fuel. The "end-effects" issue has been a pivotal concern since the proposal of burnup credit for storage and transportation of spent PWR fuel. The objective of SFSX is to provide a benchmark for criticality calculations of spent PWR fuel. Furthermore, SFSX is to provide that benchmark with a number of desirable characteristics. SFSX is to be performed at ambient temperature, eliminating moderator temperature concerns. SFSX provides not only a critical using actual spent PWR fuel, but provides a fresh fuel critical experiment as a touch point, enabling the determination of the worth of the spent fuel. SFSX also provides a benchmark for criticality calculations with axially varying fuel burnup, and a basis for the determination of the worth of the underburned ends relative to the spent fuel center sections.

The ability to accurately predict the multiplication factor for spent PWR fuel configurations depends on two critical factors: (1) accurate determination of the constituents of the spent fuel (isotopics), and (2) accurate calculation of the multiplication factor for the known isotopics and geometry. The ATM-104 material [1], briefly described below, provides chemically analyzed (known isotopics) spent PWR fuel. The isotopes for which the ATM-104 fuel was analyzed can be used precisely in comparing calculated and measured values of the multiplication factor for this benchmark critical experiment.

EXPERIMENT DESIGN

The SFSX is a fuel-replacement experiment. As such, it consists of a series of three approach-to-critical experiments. The first experiment uses only unirradiated or fresh fuel elements, described below. This provides a demonstration of the approach to critical procedures. The fresh fuel critical will provide an additional fuel benchmark. However, the

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primary benefit of this fresh fuel data point is to provide a basis for the determination of the spent fuel worth.

For the second experiment, the seven centrally located unirradiated fuel elements are replaced by spent fuel taken from the mid-sections of several of the fuel rods from the ATM-104 assembly. The center sections of the spent fuel rods are selected specifically to eliminate considerations of axial burnup variations. The burnup is relatively uniform along 50 cm near the center of the fuel rods. Replacing the fresh fuel with the spent fuel results in a decrease in multiplication, directly providing a reactivity worth of the spent fuel. Fresh fuel is added to the outside of the assembly to reach a delayed critical configuration. This configuration is the benchmark data point for calculation of a spent fuel critical.

The third experiment is similar to the second except that the spent fuel originates from the end sections of the ATM-104 fuel. The distribution of burnup effects, particularly the under-burned ends of the fuel rods, is addressed by this third measurement. Because the burnup of the end fuel section has a large gradient, this measurement, in addition to providing a comparison of the worths of end and center sections, provides a challenging benchmark for axial nodalization in criticality calculations.

Each experiment is run as a standard approach-to-critical experiment. During each approach to critical, the count rate data are collected for successively larger fuel arrays and used to generate plots of inverse multiplication factors compared to the corresponding number of fuel rods in the assembly. From the plots, estimates are made of critical fuel mass for each experiment. The fuel additions are continued until the plots indicate that the next fuel rod addition will result in a delayed critical configuration. The fuel loading at which the plots indicate that the assembly is at exactly delayed critical is the benchmark datum for the experiment. The next fuel rod is then added to obtain a fuel configuration slightly beyond delayed critical, the resultant positive period measured. The positive period is also reported and can be used with the calculated delayed neutron fraction for the assembly to obtain the multiplication factor.

The relative reactivity worth of the spent fuel can be assessed by comparing the measured delayed critical fuel loading with and without spent fuel. An analytical effort to model the experiments and anticipate the core loadings required to yield the delayed critical conditions is carried on in parallel with the experiments. The primary analytical tools are the Monte Carlo neutronics code KENO-Va and a 27-group cross-section library that includes cross sections for many fission products, both from the SCALE package of codes and data [2].

EXPERIMENT FUEL

Two types of fuel are available for the SFSX critical experiments, a large amount of unirradiated or fresh fuel, and a smaller amount of irradiated or spent fuel. The critical assemblies consist primarily of the fresh fuel which drives the spent fuel.

The fresh fuel [3] is 4.31 % enriched UO_2 pellets with an outside diameter of 1.27 cm. The fuel is clad in zircaloy-4. The height of the fuel pellet stack in the fresh fuel is nominally 50 cm.

The spent fuel sections are cut from fuel rods in assembly D047 of the Calvert Cliffs Nuclear Power Plant (Unit 1) which achieved an assembly-averaged burnup of about 42 MWd/kgM. Before irradiation in the reactor, the fuel rods consisted of 3.04 % enriched UO2 pellets with a diameter of 0.9563 cm. The rods are clad in zircaloy-4. Selected rods from this assembly were characterized at the Pacific Northwest Laboratory [1]. The fuel sections used in the SFSX are taken from the fuel rods immediately surrounding a rod, designated MKP-109, that was destructively characterized. After cutting, the spent fuel sections are placed in a second unirradiated sealed zircaloy-4 rod which prevents water infiltration to the fuel and fission product migration to the rest of the assembly.

The axial gamma scan for ^{137}Cs activity (an indicator of burnup) of rod MKP-109 is shown in Figure 1. The implied burnup is relatively flat over most of the length of the rod with the exception of about 60 cm on the ends where the burnup drops sharply. With a lower average burnup, the end sections are more reactive than the center sections. The 50-cm height of the unirradiated fuel in the SFSX assembly was chosen to give the experiment sensitivity to this relatively short region of rapidly varying burnup.

ASSEMBLY DESIGN

The SFSX is operated at Sandia's Technical Area V in the SPR Kiva which currently houses Sandia Pulsed Reactors II (SPR-II) and III (SPR-III). The metal-fueled burst reactors, SPR-II and SPR-III, are stored elsewhere during the critical assembly operations.

The SFSX is a water-moderated and -reflected assembly with the fuel rods in a 2.8-cm triangular pitch. Figure 2 shows an overall view of the SFSX hardware. The assembly tank is a right circular cylinder approximately 120 cm in diameter and 90 cm tall with a 30-cm diameter cylindrical

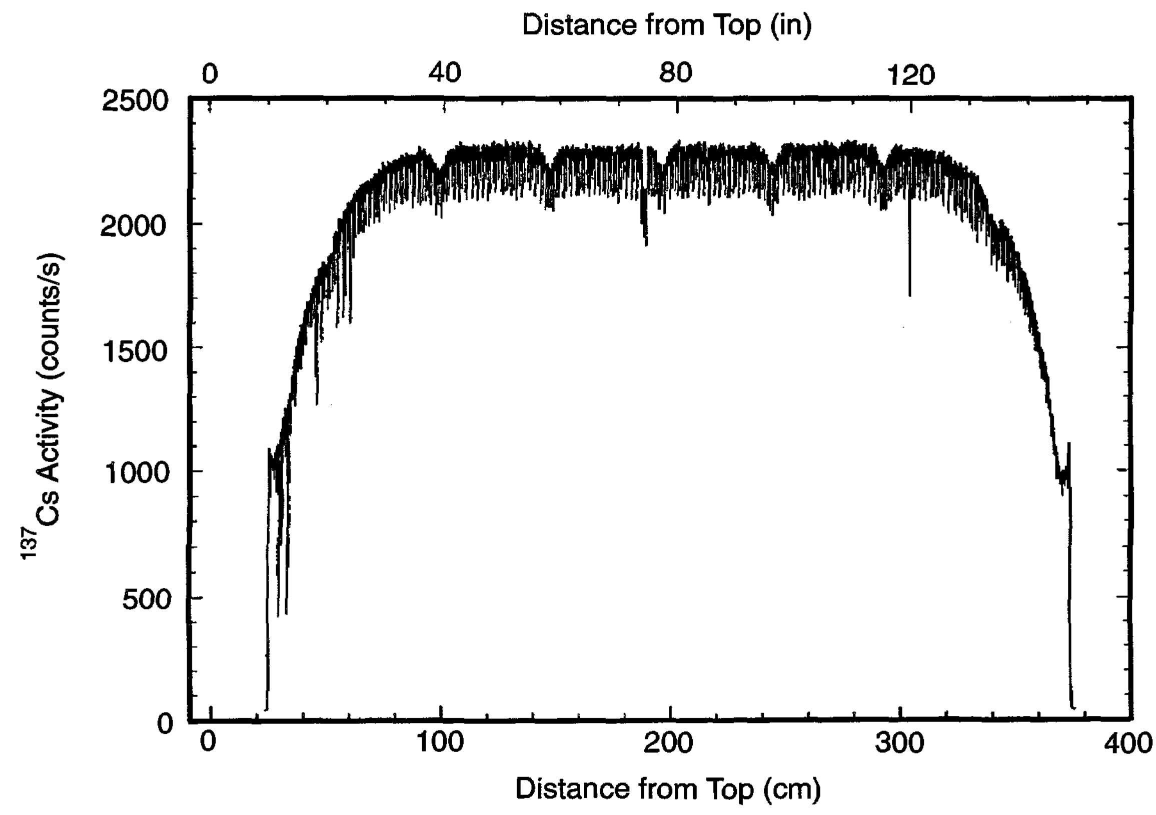

Figure 1. Axial gamma-ray scan for ^{137}Cs activity in a fuel rod from ATM-104 (Figure B.7. from [1]).

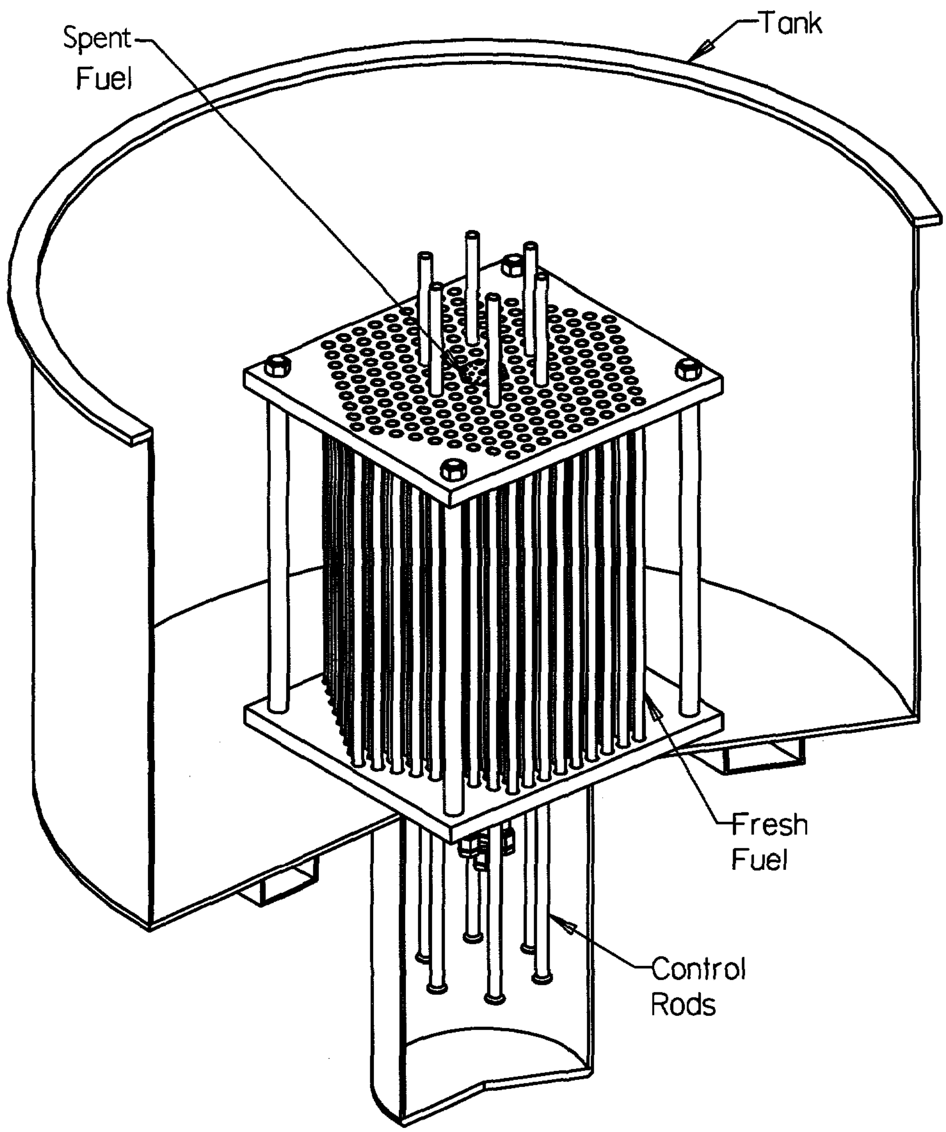

Figure 2. Overall view of the SFSX critical assembly.

projection out the bottom. The assembly fuel is supported by two 2.54-cm-thick aluminum grid plates. The top grid plate is drilled through with the grid pattern for insertion and removal of the fuel. The bottom grid plate consists of a sandwich of two 1.27-cm-thick plates, the upper one being drilled through with the grid pattern and the lower being solid to support the fuel. The spacing between the grid plates is 50 cm. The grid plates are mounted in the tank so that a water reflector of at least 10-cm thickness surrounds the assembly.

The unirradiated fuel is fabricated with a nominal 50-cm fuel height. The cladding is zircaloy-4 with a 1.27-cm-thick lower end plug and a 2.54-cm-thick upper end plug. When the fuel rods are inserted in the assembly, the top of the lower end plug is at the elevation of the top of the lower grid plate. The upper and lower edges of the upper end plug are at the same elevations as the upper and lower surfaces of the upper grid plate. As a result, the end plugs in the fresh fuel exactly fill the holes drilled in the grid plates. The assembly can be modeled as a fuel/clad/water region with solid metal plates above and below surrounded by a water reflector.

The assembly grid plates have hexagonal holes machined in them that remove the central seven fuel rod positions. During the critical experiment using all fresh fuel, these holes are filled by 2.54 cm thick auxilliary grid plates that complete the grid pattern. The auxilliary grid plates are removed during experiments that include spent fuel. The seven spent fuel rod sections are mounted in a bundle with upper and lower grid plates that fit in the hexagonal holes in the assembly grid plates. The spent fuel bundle is attached to an actuating mechanism that moves the bundle from the center of the assembly down into the projection in the bottom of the assembly tank. The spent fuel bundle is driven to this lower position at times when personnel are in the assembly area to reduce radiation levels in the vicinity. Figure 3 shows a view of the assembly from below with the spent fuel bundle partially driven out of the assembly.

During operation, the assembly is controlled by six identical fuel-followed control rods. The control rods are attached through independent electromagnets in pairs to

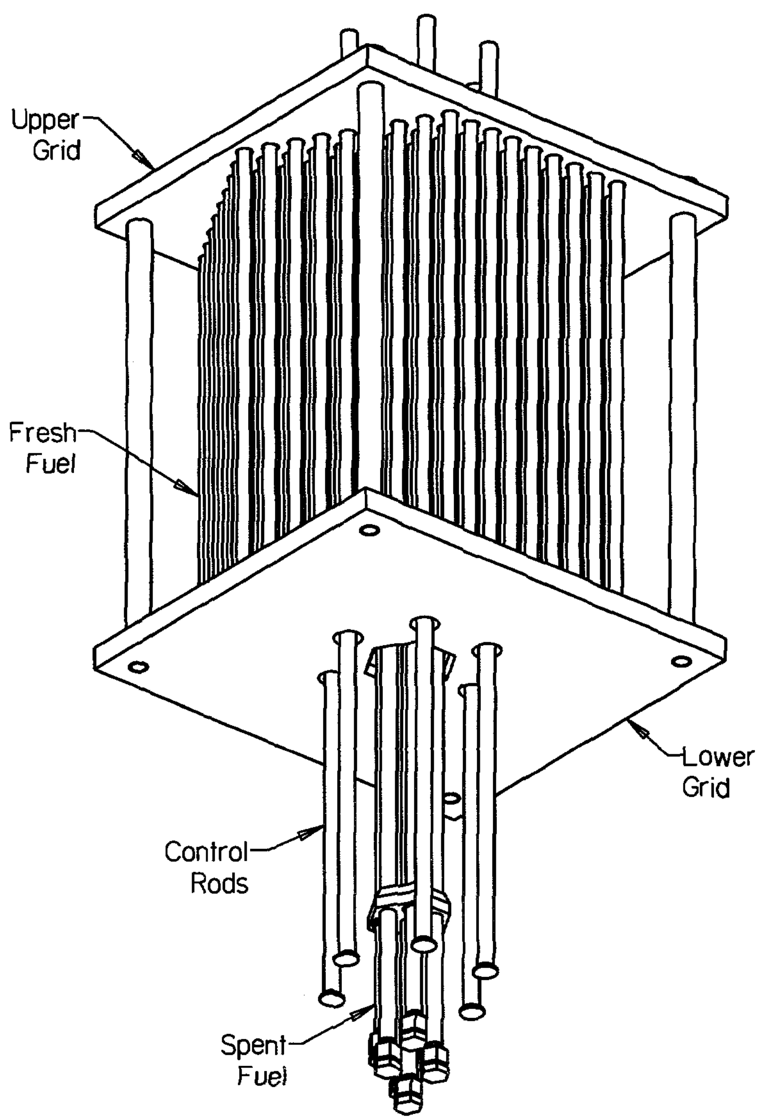

Figure 3. View of the SFSX critical assembly from below showing the spent fuel bundle.

three control element drives. Each control rod drops independently during an assembly scram. The control rods have a lower fueled section that matches the grid plate-fuel-grid plate configuration of the rest of the assembly. Above the fueled section is a 10-cm-thick polyethylene section below a 50-cm boron-carbide absorber section. The polyethylene is included to decouple the absorber section from the assembly with the control rods fully raised. With a control rod up, the grid position occupied by the control rod is nearly identical to one occupied by a fresh fuel rod.

RESULTS

Several parameters of the SFSX critical assemblies were calculated using the SCALE code and cross-section package [2]. These parameters, for both critical assemblies that include spent fuel, are shown in Table I. The first line of the table gives the smallest total number of grid locations occupied by both fresh and spent fuel rods when the assembly exhibits a positive period. The third and succeeding lines give Δk/k's (reactivities) for several modifications to the assembly fuel. These data can be used as figures of merit for the assemblies. The second line gives the reactivity worth of an incremental fresh fuel rod which can be used to translate the reactivities given in the following table lines into array size increments.

The third line of Table I gives the reactivity difference produced by replacing the spent fuel bundle with assembly fresh fuel. The fourth line shows the sensitivity of the assembly to the difference between the spent fuel center sections and the end sections. The fifth line in the table gives the reactivity effect of removing the fission products from the spent fuel, thus showing the capability of the assemblies to detect the difference between taking full burnup credit and taking credit only for fissile material depletion including actinide buildup. The sixth line shows the reactivity effect of removing the fission products and the absorbing plutonium isotopes, the difference between full burnup credit and assuming only fissile depletion and fissile plutonium buildup.

Table I. SFSX Calculated Parameters

	Parameter	Seven Spent Fuel Centers	Seven Spent Fuel Ends
	Total Grid Locations Occupied at DC+[a]	156	154
	Incremental Fresh Fuel Rod Reactivity Worth at DC+ (%)	0.134	0.136
Δk/k (%)	Replace Spent Fuel with Assembly Fresh Fuel	3.41 ± 0.06	3.08 ± 0.06
	Replace Spent Fuel Center Sections with End Sections	0.30 ± 0.04	
	Remove Fission Products	0.62 ± 0.04	0.56 ± 0.04
	Remove Fission Products and Absorbing Plutonium Isotopes	0.99 ± 0.04	0.72 ± 0.04
	Replace Spent Fuel with Fresh PWR Fuel	1.97 ± 0.05	1.65 ± 0.05

Array size at DC+ with all assembly fresh fuel: 131
Incremental fresh fuel rod reactivity worth at DC+: 0.167%
[a] DC+ is the smallest array expected to be supercritical

The final line in the table gives the reactivity effect of replacing the spent fuel with unburned PWR fuel (the composition of the test fuel before it was irradiated).

The calculated results in Table I show that the SFSX critical experiments have sufficient sensitivity to detect the fission products in the spent fuel (a 0.60 % reactivity difference is more than four fresh fuel rods difference in the array size). This is the difference between the full burnup credit model and the model that assumes only fissile depletion and actinide buildup.

The SFSX assemblies are flexible and can be used to perform many other critical experiments. Experimental parameters that could be varied are the fuel rod pitch (to vary the neutron spectrum), the number of spent rods in the bundle, and the type of spent fuel used (e.g. different burnup). The assemblies can also be used to address the effects of individual fission products by inserting fuel rods doped with the fission product of interest.

CONCLUSIONS

The SFSX provides a direct measurement of the reactivity effects of spent fuel using a well-characterized, spent fuel sample (ATM-104). The SFSX provides an experimental measurement of the end-effect, i.e., the reactivity effect of the variation of the burnup profile at the ends of the fuel rods. The design of SFSX is optimized to yield accurate benchmark data for the effects of interest. The reactivity effects of the spent fuel fission products, as well as the end effects, can be measured well above experimental uncertainties.

The SFSX is a fuel-replacement experiment designed to measure the critical array size for three fuel configurations. The first configuration includes only unirradiated fuel. The second includes a seven-rod bundle of fuel sections cut from the center of a PWR fuel assembly where the burnup is relatively constant. The third configuration includes a seven-rod bundle of fuel sections from the ends of a PWR fuel assembly with steeply varying burnup. The composition of both fuel types is well known, having been measured previously.

The measured array size data constitute integral benchmark data against which the codes and data used to perform criticality calculations on spent nuclear fuel containers can be tested.

ACKNOWLEDGMENTS

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